UTILITY ADVANCED TURBINE SYSTEMS PROGRAM (ATS)

TECHNICAL READINESS TESTING AND

PRE-COMMERCIAL DEMONSTRATION

CONTRACT NO. DE-FC21-95MC32267

FINAL

QUARTERLY TECHNICAL PROGRESS REPORT TPR-21
For the Period April 1, 2001 to June 30, 2001

to the

U.S. DEPARTMENT OF ENERGY

Office of Fossil Energy

National Energy Technology Laboratory

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Submitted by

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ABSTRACT

The objective of the ATS program is to develop ultra-high efficiency, environmentally superior and cost competitive gas turbine systems for base load application in utility, independent power producer and industrial markets. Specific performance targets have been set using natural gas as the primary fuel:

- System efficiency that will exceed 60%(lower heating value basis) on natural gas for large scale utility turbine systems; for industrial applications, systems that will result in a 15% improvement in heat rate compared to currently available gas turbine systems.
- An environmentally superior system that will not require the use of post combustion emissions controls under full load operating conditions.
- Busbar energy costs that are 10% less than current state-of-the-art turbine systems, while meeting the same environmental requirements.
- Fuel-flexible designs that will operate on natural gas but are capable of being adapted to operate on coal-derived or biomass fuels.
- Reliability-Availability-Maintainability (RAM) that is equivalent to the current turbine systems.
- Water consumption minimized to levels consistent with cost and efficiency goals.
- Commercial systems that will enter the market in the year 2000.

In Phase I of the ATS program, Siemens Westinghouse found that efficiency significantly increases when the traditional combined-cycle power plant is reconfigured with closed-loop steam cooling of the hot gas path. Phase II activities involved the development of a 318MW natural gas fired turbine conceptual design with the flexibility to burn coal-derived and biomass fuels. Phases I and II of the ATS program have been completed. Phase III, the current phase, completes the research and development activities and develops hardware specifications from the Phase II conceptual design.

This report summarizes Phase III Extension activities for a three-month period. Additional details may be found in monthly technical progress reports covering the period stated on the cover of this report. Background information regarding the work to be completed in Phase III may be found in the revised proposal submitted in response to A Request for Extension of DE-FC21-95MC32267, dated May 29, 1998 and the Continuing Applications of DE-FC21-95MC32267, dated March 31, 1999 and November 19, 1999.

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EXECUTIVE SUMMARY

The objective of the ATS program is to develop ultra-high efficiency, environmentally superior and cost competitive gas turbine systems for base load application in utility, independent power producer and industrial markets. In Phase I of the ATS program, Siemens Westinghouse found that efficiency significantly increases when the traditional combined-cycle power plant is reconfigured with closed-loop steam cooling of the hot gas path. Phase II activities involved the development of a 318 MW natural gas fired turbine conceptual design with the flexibility to burn coal-derived and biomass fuels. Phases I and II of the ATS program have been completed. Phase III, the current phase, completes the research and development activities and develops hardware specifications from the Phase II conceptual design. This report summarizes Phase III activities for the three month period April 1, 2001 to June 30, 2001.

Phase 3 Extension originally involved no load testing of the ATS turbine generator. A redefinition of Phase 3 Extension tasks was submitted as a continuing application to the Department of Energy on March 31, 1999. The continuing application continues to focus on critical engineering, manufacturing, development and testing to verify the readiness of ATS technology for commercial application. Approval of the continuing application was received in June 1999. A second continuation application was submitted in November 1999.

Additional analyses were completed on the vane cascade components and the Final Design Review was successful. All materials were ordered and vane cascade component hardware fabrication has been started.

For the blade root verification program, STC are ready to instrument the test disc once Hamilition has completed the disc broaching. Testing of the disc will have to be completed after the ATS program ends.

Rope seals were incorporated into the stage 2 and 3 vane assemblies in the Millenium W501G engine. Investigations into a second source for brush seals are underway. Sulzer completed abradability tests and preliminary analysis indicate that porosity increase in the current PWA 281 coating can help abradability.

Tests are in progress to characterize material properties, sintering, etc. Additional test at Waltz Mill confirmed previous results. Design review on the TBC Lifing Model will be held in September. Work is in progress to incorporate TBC and MCrAlY thermo-mechanical properties into M-Vision.

New experiments are being conducted to qualify the Meandering Wave Magnetometer on coated parts for diffused coating thickness measurements. The pulsed thermal wave imaging technique was successfully applied for detecting debonds on diffusion-bonded transitions. Johns Hopkins University has successfully demonstrated the X-ray diffraction technique for detecting secondary crystals and determining crystal orientation on SX components.

The following IN939 tests are now complete: 7 uncoated; 9 with bondcoat and TBC; 13 with

bondcoat only.

Examination of seven BFH coated ring segments with ~20,000 hours of operation revealed varying degrees of degradation. Better understanding of BFH processing is required to further develop the material system.

Phase 2 testing of PWA 1483 SX material has been completed. Creep rupture testing has begun on the Phase 3 rejuvenation study.

Due to the identification of a lower cost alternative the NASA Glenn Research Center test rig will not be used for the High Pressure Burner Rig testing of BFH. Results of recent W501D5 engine testing have shown the thermal limit of BFH may be lower than originally believed.

Results of the fifth and sixth casting trials conducted by PCC were reviewed. One of the 3 molds in trial 6 had run-out. Two were filled 100% and 99%.

Module #3 performed significantly better than Module #2. The mechanical design changes appear to have fixed the warping issues. At ATS firing temperature NOx emissions were 13 ppm and combustor dynamic pressures were very low. Preparations are underway for testing Module #3 and #4 at DLR. Negotiations on the Development/Commercial Supply Agreement with Catalytica have stalled. The module demonstration test is continuing, however.

INTRODUCTION

BACKGROUND

The National Energy Strategy (NES) calls for a balanced program of greater energy efficiency, use of alternative fuels, and the environmentally responsible development of all U.S. energy resources. Consistent with the NES, an U.S. Department of Energy (DOE) program has been created to develop Advanced Turbine Systems (ATS). The Siemens Westinghouse ATS Program is funded and directed by DOE's National Energy Technology Laboratory (NETL). The technical ATS requirements are based upon two workshops held in Greenville, SC that were sponsored by DOE and hosted by Clemson University. The objective of this 8-year program, managed jointly by DOE's Office of Fossil Energy and Office of Conservation and Renewable Energy, is to develop natural-gas-fired base load power plants that will have cycle efficiencies greater than 60%, based on lower heating value (LHV), be environmentally superior to current technology and also be cost competitive. The program will include work to transfer advanced technology to the coal-and biomass-fueled systems being developed in other DOE programs.

METHODOLOGY

The Advanced Turbine Systems program is structured into four elements:

- Innovative Cycle Studies
- Utility Advanced Turbine Systems
- Industrial Advanced Turbine Systems
- Technology Base

Within each program element there are several planned phases. For example, the Innovative Cycle Studies element includes two phases.

- Program Definition/Planning Studies
- Concept Development

The objective of the ATS Program is to develop ultra-high efficiency, environmentally superior, and cost-competitive gas turbine systems for base-load application in utility, independent power producer, and industrial markets. Specific performance targets have been set using natural gas as the primary fuel:

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- An environmentally superior system that will not require use of post-combustion emissions controls under full-load operating conditions.
- Busbar energy costs that are 10% less than current state-of-the-art turbine systems, while meeting the same environmental requirements.
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This report summarizes Phase III extension activities for a three month period. Additional details may be found in monthly technical progress reports covering the period stated on the cover of this report. Background information regarding the work to be completed in Phase III may be found in the revised proposal submitted in response to A Request for Extension of DE-FC21-95MC32267, dated May 29, 1998 and the Continuing Applications of DE-FC21-95MC32267, dated March 31, 1999 and November 19, 1999.

RESULTS AND DISCUSSION

11.0 PROGRAM MANAGEMENT

There were no scheduled activities for this quarter.

12.0 DEVELOPMENT ENGINEERING

12.1 VERIFICATION TESTS

Vane Cascade Additional analyses were completed on the vane cascade components and the Final Design Review was successful. All materials were ordered and vane cascade component hardware fabrication has been started. Agilis started work on the sidewall vane thermo-mechanical analysis. AEDC resumed design work on the additional systems required for the vane cascade test.

Turbine Root Blade Verification STC are ready to instrument the test disc once Hamilition has completed the disc broaching. Testing of the disc will have to be completed after the ATS program ends.

Turbulator Model Tests No scheduled progress to report.

12.2 C. T. ENGINE DEVELOPMENT ENGINEERING

Combustion System Development ATCC3 Module #3 was tested at Solar Turbines in San Diego and performed significantly better than the first two modules. The mechanical design changes appear to have fixed the warping issues. At ATS firing temperature NOx emissions were 13 ppm and combustor dynamic pressures were very low. Lower firing temperatures yielded lower NOx emissions but higher than allowable dynamic pressures at some test points. Plans were made for testing of ATCC Modules #3 and #4 at full pressure (15 bar) in July. A review of the combustor design was held with Agilis on June 15th. Vibration and manufacturability were the main concerns. However, the design was accepted for initial combustion testing.

Advanced Seal Development

Rope Seal Rope seals have been incorporated into the stage 2 and 3 vane assemblies in the Millennium W501G engine. Thermocouple and flow measurements will be made to obtain information on seal performance.

Brush Seal Development Investigations of a second source for brush seals are underway.

Abradable Coating Development Sulzer completed abradability tests. Preliminary analyses indicate that porosity increase in the current PWA 281 coating can help abradability. Erosion tests at Cincinnati University are on hold until abradability tests on a new system are completed. For the short term, the porosity of the current system and CBN particle size for blade tip treatment will be increased. For the long term, testing will be conducted on a new coating invented by SWPC, which has very low porosity that can be increased to aid abradability.

Labyrinth Seal Guardian Labyrinth Seal are changing seal material from 410 St. Stl. to Nitronic (modified St. Stl.). A scrap W501FD disc is being machined for testing, which will be completed by the end of June. Testing to be conducted by Turboparts.

12.3 MATERIALS DEVELOPMENTAL ENGINEERING

Steam Effects on Materials The need for conducting mechanical tests in steam was established by data from literature survey. Different designs for test fictures and mechanical test samples were evaluated. Quotes for mechanical testing in steam are being solicited.

Production Support of SX Casting The fifth and sixth casting trial of just the airfoils were completed. The cut up mold from the sixth casing trial showed cracks caused during mold firing. Plans were formulated to overcome the mold-cracking problem. A seventh casting trial is planned for August.
Accu-Cut received the S.C. inner shrouds and is working on the plunge EDM electrode.

Advanced Vane Alloy Final report on the Advanced Vane Alloy Program, ATS Task 12.3.8, was issued on May 30, 2001. The report number is TR-01060.

TBC Life Prediction Tests are in progress to characterize material properties, sintering, etc. Additional tests at Waltz Mill confirmed previous results. Design review on the TBC Lifing Model will be held in September. Work is in progress to incorporate TBC and MCrAlY thermo-mechanical properties into M-Vision. Proposal was submitted to DOE for a three-year program on EB-PVD lifing. Investigating a lower cost facility in Germany suitable for low temperature (up to 2200 to 2300 deg. F) test. High temperature test will have to use the Waltz Mill rig.

ATS NDE The **Meandering Winding Magnetometer (MWM)** is being gradually accepted by other Siemens NDE groups. New experiments are being conducted to qualify the MWM process on coated parts for diffused coating thickness. A multi-channel, multi-frequency MWM is also being developed for Tungsten Carbide coated Titanium blades. The **pulsed (flash) thermal wave imaging technique** was successfully applied for detecting debonds on diffusion-bonded W501G transitions at Houston Service Center. The technique was also applied to detecting various TLP bonding defects on the experimental SX TLP bonded vane design. Johns Hopkins University has successfully demonstrated the **X-ray diffraction technique** for detecting secondary crystals and determining crystal orientation on SX components. However, a high-power X-ray source still needs to be located for the full-scale volumetric examination (T/T Laue) on real turbine blades and vanes.

TMF Testing Row 1 Blade Alloy PWA 1483 TMF test pieces have been coated by TACR and are available for testing at Cincinnati University. The following IN939 TMF tests are now complete: 7 uncoated; 9 with bondcoat + TBC; 13 with bondcoat only.

Ring Segment Abradable Coating Development Examination of seven BFH coated ring segments after ~20,000 hours of operation in a W501D engine revealed varying degrees of degradation. The 3mm thick BFH coatings were rubbed by the un-tipped blades and within the wear track the BFH was not well retained. The 2mm thick BFH coatings showed no sign of blade contact but contained varying levels of degradation from pockets of honeycomb with no backfill to virtually undamaged areas. Better understanding of processing of BFH is required to further develop the material system.

Alternate Alloy Development The Phase 2 tensile, creep rupture and low cycle fatigue testing of PWA 1483 SX material has been completed. Differential Thermal Analysis for the Phase 2 heat treatment effect study has been completed. Creep rupture testing has begun on the test specimens for Phase 3 rejuvenation study. The Luyan de Cuyo PWA 1483 service blades heat-treated by DPC have been examined for grain recrystallization.

BFH for Hot Walled Combustors Due to the identification of a significantly less expensive source of rig testing and questions about the suitability of the NASA Glenn Research Center test rig we will not be proceeding with the High Pressure Burner Rig testing of BFH by NASA. Results of the recent W501D5 engine testing of BFH have shown that the thermal limit of BFH may be lower than originally believed. A modified program plan is being prepared to conduct a

detailed investigation to better understand the mechanism of high temperature degradation of BFH.

12.4 C. T. MANUFACTURING ENGINEERING

Row 1 Blade and Vane Alternative Design Results of the fifth and sixth casting trials conducted by PCC were reviewed. Two of the 3 molds in the sixth casting trial filled 100% and 99%. One mold had run-out. After modifications to strengthen the mold, Trial 6E (the one that produced the good casting) will be repeated. Accu-Cut was selected to perform the wire slicing of the shrouds.

12.5 GENERATOR DEVELOPMENTAL ENGINEERING

ATS Class G Stator Development. No scheduled activity.

12.6 ADAPTATION TO COAL AND BIOMASS FUELS

The draft topical report describing the ATS turbine in coal-fueled applications was transmitted to DOE.

13.0 C. T. MANUFACTURING DEVELOPMENT AND TOOLING

13.1 DELETED

13.2 MANUFACTURING & TOOLING DEVELOPMENT ENGINEERING

No scheduled activity.

13.3 DELETED

13.4 MANUFACTURING VERIFICATION TESTS

No scheduled activity.

14.0 ATS TECHNOLOGY VERIFICATION PROGRAM

14.1 STEAM COOLED COMPONENT & AERO-THERMAL DESIGN VALIDATION TEST

Task is complete.

14.2 ADVANCED VISCOUS COMPRESSOR TEST

Task is complete.

14.3 CATALYTIC COMBUSTOR TEST

ATCC—Testing of Module #3 at Solar Turbines was limited to 10 bar due to flow limitations. Module #3 performed significantly better than Module #2. Preparations are underway for testing Module #3 and #4 at DLR. Setup and testing is scheduled for the first three weeks of July. The preliminary full combustor design has been completed at Agilis. Upon completion of a successful peer review, work will begin with the goal of having a full combustor test by the end of the year.

Catalytica—Negotiations on the Development/Commercial Supply Agreement with Catalytica have stalled. The module demonstration test is continuing, however. A meeting was held with Isler to begin design work on the new test rig for the module testing.

14.4 STEAM COOLED VANE TEST

No scheduled activity.